ANALYSIS OF HYDROGEOLOGIC DATA FROM AN OBSERVATION WELL AT MIRROR LAKE (COLUMBUS, OHIO)

Senior Thesis

Submitted in partial fulfillment of the requirements for the

Bachelor of Science Degree

At The Ohio State University

By

Michael J. Madson

The Ohio State University

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Approved by

Audrey H. Sawyer, Project Advisor

School of Earth Sciences

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Abstract

Limestone aquifers are important sources of drinking water in many regions of the United States, including Ohio. Here, I characterize properties of a limestone aquifer using data from an observation well that was installed as part of the Mirror Lake Water Science Learning Lab on The Ohio State University campus in Columbus, Ohio. I integrate drilling observations, a gamma ray log, and borehole camera footage to identify geologic formations and conductive features within the limestone. I also analyze slug test and pump test results to determine aquifer hydraulic conductivity. I show that the hydraulic conductivity is comparable with other local measurements and within the range of many limestone aquifers from other regions. I present three months of water level, temperature, and specific conductivity data from the observation well to explore the factors that influence water level and water quality in the limestone aquifer.

Acknowledgements

To Jameson Drilling, whose donation of this groundwater well made this research possible. Funds for this project were also provided through NSF EAR 1752995.

A special thanks to my research advisor, Dr. Audrey Sawyer for her guidance and support in forming this thesis.

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I thank Jim Raab with ODNR for his help in collecting the gamma log at the well.

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I am also grateful to Michael Deal with Ohio EPA for capturing down-hole footage of our well.

Thank you to Andy Baker with In-Situ Inc. for his assistance with repairing the telemetry box and trouble shooting.

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Introduction

Groundwater is an important water resource that is often overlooked in humid regions with high annual precipitation such as Ohio. Despite an approximate annual precipitation of 30-44 inches/year in Ohio (Ohio EPA, 2014), nearly half of Ohio citizens and businesses rely on groundwater wells for their water resource needs (Ohio EPA, 2014). More than a third of Ohio's bedrock geology consists of limestone (Slutcher et al, 2006), so it is not surprising that about half of groundwater used in Ohio is supplied from limestone aquifers (Ohio EPA, 2014). Because limestone is soluble in water, the limestone aquifers in Ohio are characterized by conductive fractures and dissolution features that contribute to highly heterogeneous aquifer properties and chemical transport timescales. Due to the complex effects on contaminant transport, this heterogeneity is important to study and understand in the context of Ohio limestone aquifers.

In 2018, The Ohio State University established the Mirror Lake Water Science Learning Laboratory to expose students to the hydrogeology of Columbus's limestone aquifers and the importance of groundwater as a water resource. For this purpose, Jameson Drilling donated a groundwater observation well on March 1st 2018 that would serve as the centerpiece for the Learning Lab. While other boreholes have been drilled on the South Oval for geothermal investigations and to install a seismometer beneath Orton Hall, the new observation well is dedicated to education and research and is accessible for data collection and hydrogeologic investigation. Here, I characterize the hydrogeology of the new observation well using a combination of approaches, including borehole geophysics and aquifer testing. I then compare my interpretations with observations from other wells.

STUDY AREA

Local Geology

The Ohio State University campus in Columbus, Ohio is underlain by extensive limestone deposits that range in age from Silurian through Devonian (Figure 1) (Schmidt, 1958). The Columbus Limestone is gray to brown with massive bedding. The upper portion is characterized as a fossiliferous, gray limestone, while the lower third is a brown dolomite. The unit thickness ranges up to 105 feet thick (Slutcher et al, 2006). The overlying Delaware Limestone is gray to brown in color with thin to massive bedding. Nodules and layers are reported, as is a carbonaceous, petroliferous odor. The Delaware Limestone is up to 45 feet thick (Slutcher et al, 2006). The Columbus and Delaware Limestone units generally dip to the East and have local outcrops along the Scioto River (Figure 1). East of the Olentangy River, the limestone units are overlain by the Olentangy Shale. A major unconformity separates limestone and shale from overlying glacial till and Holocene age gravel deposits (Figure 1) (Schmidt, 1958).

Mirror Lake, which lies on The Ohio State University's "South Oval", is located in the Upper Scioto watershed. The average annual rainfall in the watershed is about 38 inches (Ohio EPA, 2014). Mirror Lake is located in a topographically low region that was probably created by dissolution and collapse of the Columbus Limestone (Schmidt, 1958). Water from Mirror Lake drains to the Olentangy River through storm drains during major precipitation events. Mirror Lake was historically spring-fed (Goldsmith et al, 2013). In 1935, the lake bottom was paved with brick and in later decades was heavily modified with a cement liner. The original spring flow to the lake was cut off by sewer construction (Goldsmith et al, 2013), but storm water and produced groundwater were used to augment lake levels. From 2016 to 2018, the lake area was renovated to restore more natural aquatic vegetation and improve water quality. The concrete liner of the lake was replaced with a clay liner. The Mirror Lake Water Science Learning Lab was established as part of the renovation of the lake (Figure 2).

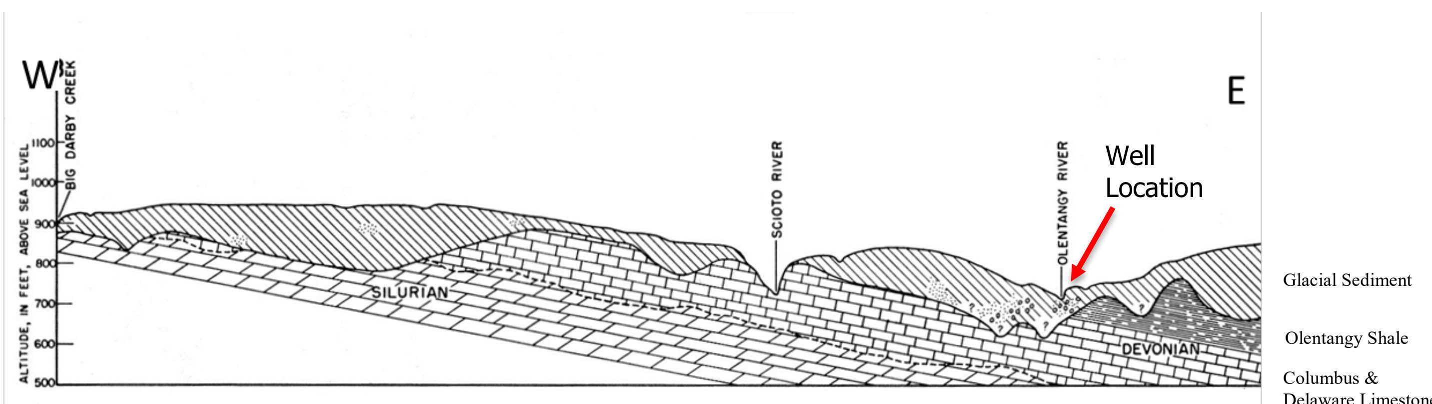

Figure 1: Geologic cross section of the western half of Franklin County (Schmidt, 1958)

Methods

Geologic and Geophysical Characterization

Drilling records were obtained from the observation well drilled on March 1, 2018 (39.997731 N / 83.013119 W, Figure 2). On April 9, 2018, a gamma ray log was collected at the observation well. The gamma log records natural radiation from surrounding rocks. On August 14, 2018, a down-hole camera was used to view the inside of the well to the bottom of the borehole. Together, the driller's log, gamma ray log, and down-hole camera recording were used to interpret the lithology at various depths in the borehole. The down-hole camera recording was also examined for features such as vugs, borehole breakouts, and fractures that could serve as conduits for groundwater flow.

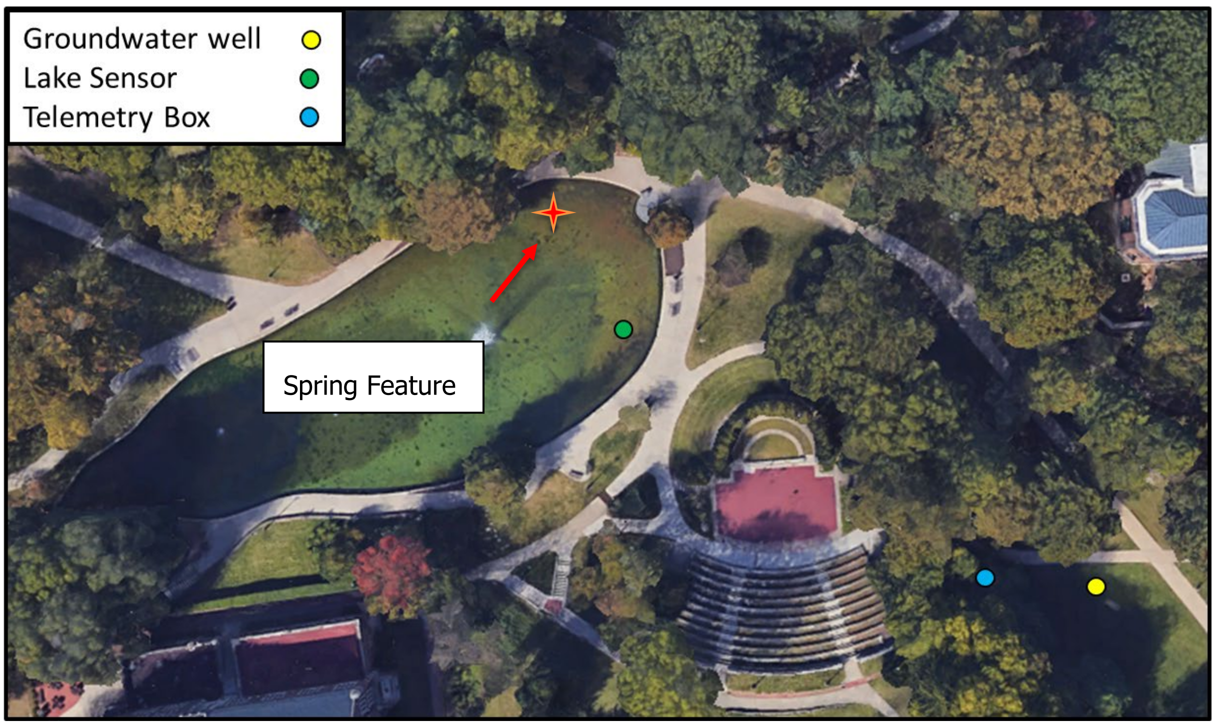

Figure 2: Area of study at Mirror Lake and infrastructure associated with the Water Science Learning Laboratory.

Aquifer Testing

On February 13, 2019, slug tests were conducted. The slug was constructed from 3.25" pvc pipe cut to 152.4 in long and filled with sand in order to ensure the slug would sink. The sealed slug was tied to a length of rope to lower the slug into the well. Before slug testing, a vented pressure-temperature sensor (In-Situ Level Troll-200) was programmed to record at a logging rate of 0.25 seconds and placed in the well. A series of two positive and two negative slug tests were then conducted where the slug was quickly lowered to the point of submersion in the well (slug-in), held in place while the water level re-equilibrated, and then raised out of the water (slug-out). Water level changes were monitored with an electrical line to verify that slug tests were run to completion.

Slug tests were analyzed using the Hvorslev method (Horslev, 1951) for hydraulic conductivity, as described by Fetter (2014). This method assumes a homogeneous, confined aquifer of infinite extent. The method also assumes that hydraulic head in the vicinity of the well is initially uniform (there is no flow).

On February 27, 2019, a pump-recovery test was conducted in the observation well using a Grundfos submersible 3" pump (SQ series) with rated capacity of 15 gal/min. Prior to the pump test, a vented pressure-temperature sensor (In-Situ Level Troll-200) was installed in the borehole and programmed with a logging interval of 1 minute. The sensor logged background water levels for 21.58 hours before the start of the test. The well was pumped for a total of 1 hour and 30 minutes at an average pumping rate of ~17.4 gal/min. Produced water was discharged to Mirror Lake through 300 feet of irrigation tube. A cumulative flow meter at the end of the irrigation tube was used to monitor the flow rate, and occasional checks were also performed with a 5-gallon bucket and stopwatch. Water quality was monitored using a YSI multi-parameter probe deployed in a 5-gallon bucket that was allowed to continuously overflow with produced groundwater. Drawdown was measured manually using an electrical line to augment sensor data. Before stopping the pump, the logging interval on the pressure-temperature sensor was increased to 1 second. Once the pump was stopped, residual drawdown was monitored for 45 minutes using sensor data and occasional electrical line measurements.

Data from the pump test were used to estimate a hydraulic conductivity value for the aquifer using the Theis solution for a confined aquifer in Aqtesolve (Theis, 1935). The Theis solution assumes a homogeneous, confined aquifer of infinite areal extent and that the well is fully penetrating. Because there was no monitoring well for the pumping test, specific storage cannot be estimated with reasonable accuracy.

Sensor Data

In August, 2018, two vented In-Situ Aqua Troll 200 sensors were installed in the monitoring well at a depth of ~20 m below the top of casing and in Mirror Lake (Figure 2). The sensors were attached to an In-Situ Cube-300 telemetry system, which transmits readings to a perpetual website at https://www.hydrovu.com/. Cables were fully trenched and protected in conduit. The sensors were programmed to monitor water depth, temperature, specific conductivity, and total dissolved solids every 15 minutes. The top of the well and lake level were surveyed with a Nikon Total Station in order to relate measured water depths to hydraulic head values. In survey measurements, the top of the casing was assigned an approximate elevation of 217 m based on readings from a handheld GPS.

Both groundwater and lake sensors provide the opportunity to compare changes in water level and water quality over time. Unfortunately, the data logger was vandalized on January 1, 2019 and is currently under repair. The records from the 3-month period spanning August 25th, 2018 to December 31, 2018 are presented.

Results

Well Design and Lithology

The well was drilled to 120 ft and cased from the surface to 70 ft (Appendix A). The gamma log is generally elevated within the cased interval, particularly within the Olentangy Shale (36 ft to 66 ft from the top of casing) (Figure 3). Gamma ray values below the Olentangy Shale are consistently low. There is a slight increase with depth at about 75 ft, which could be attributed to the change in lithology from the Delaware Limestone to the Columbus Limestone. The gamma ray curve is generally similar to expectations based on the known lithology of the area.

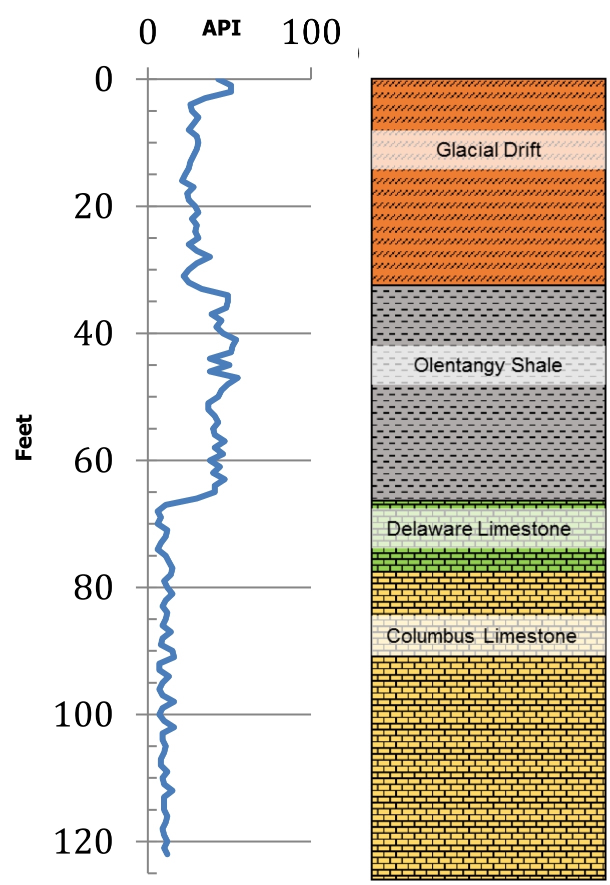

Figure 3: Gamma log and interpreted lithology. Units are recorded in API units which can be related to more familiar units by the following relationship: 1 μR/hr = 10 API.

The borehole camera footage over the uncased interval shows light grey limestone with a difference in color from darker grey to a light grey that is representative of a lithology change occurring at a depth of 77 ft (23.5 m) from the top of casing (Figure 4). There are also fractures and void spaces in the borehole. A prominent example of void space can be seen at 116 ft (35.35 m) (Figure 5). Voids at the bottom of the borehole may be responsible for water strikes reported in the driller's log near 118 ft.

Figure 4: Lithology change from Delaware Limestone to Columbus Limestone.

Figure 5: Void space in lower region of borehole.

Aquifer Testing

Hydraulic conductivity (K) values estimated from slug tests (Figure 6) using an assumed aquifer thickness of 15 meters (the length of open borehole) and the Hvorslev solution indicated an average value of 2.75×10^{-2} cm/s, with a range of 2.71×10^{-2} to 2.78×10^{-2} cm/s for the four individual slug recoveries. For comparison, the estimated K from the pump test (Figure 7) was 1.32×10^{-2} cm/s for the drawdown and recovery period (Figure 8). Estimates from slug and pump tests are within 2-fold of one another and lie within the expected range for karst limestone aquifers of 10^{-4} to 10^{0} cm/s (Frost and Cherry, 2001).

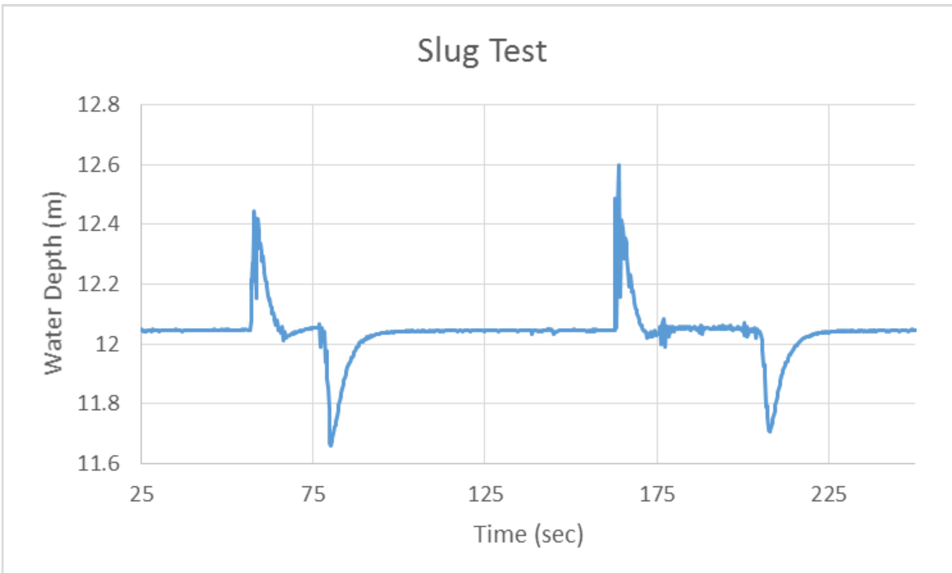

Figure 6: Slug test results used to calculate a K value of 2.75×10^{-2} cm/s

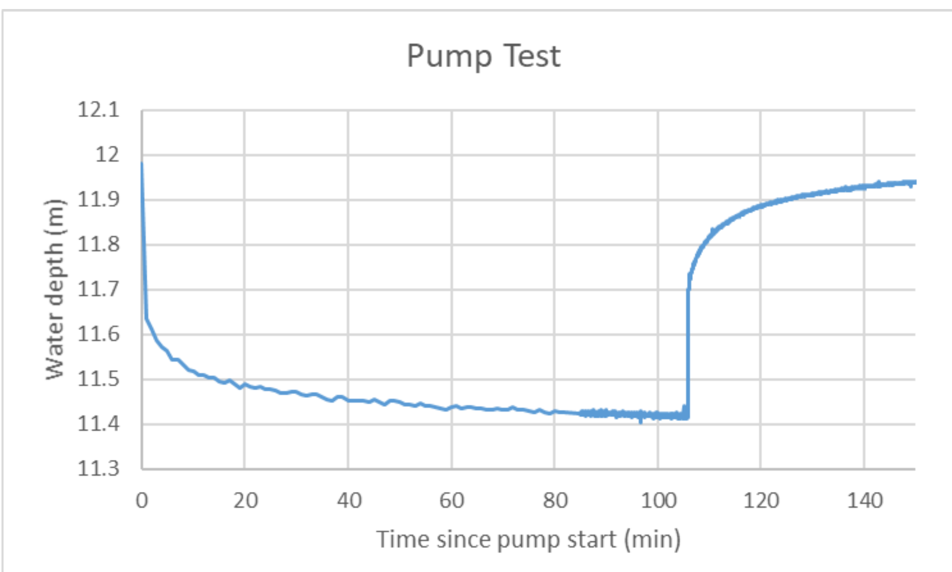

Figure 7: Pump test results used to calculate a K value of 1.32×10^{-2} cm/s

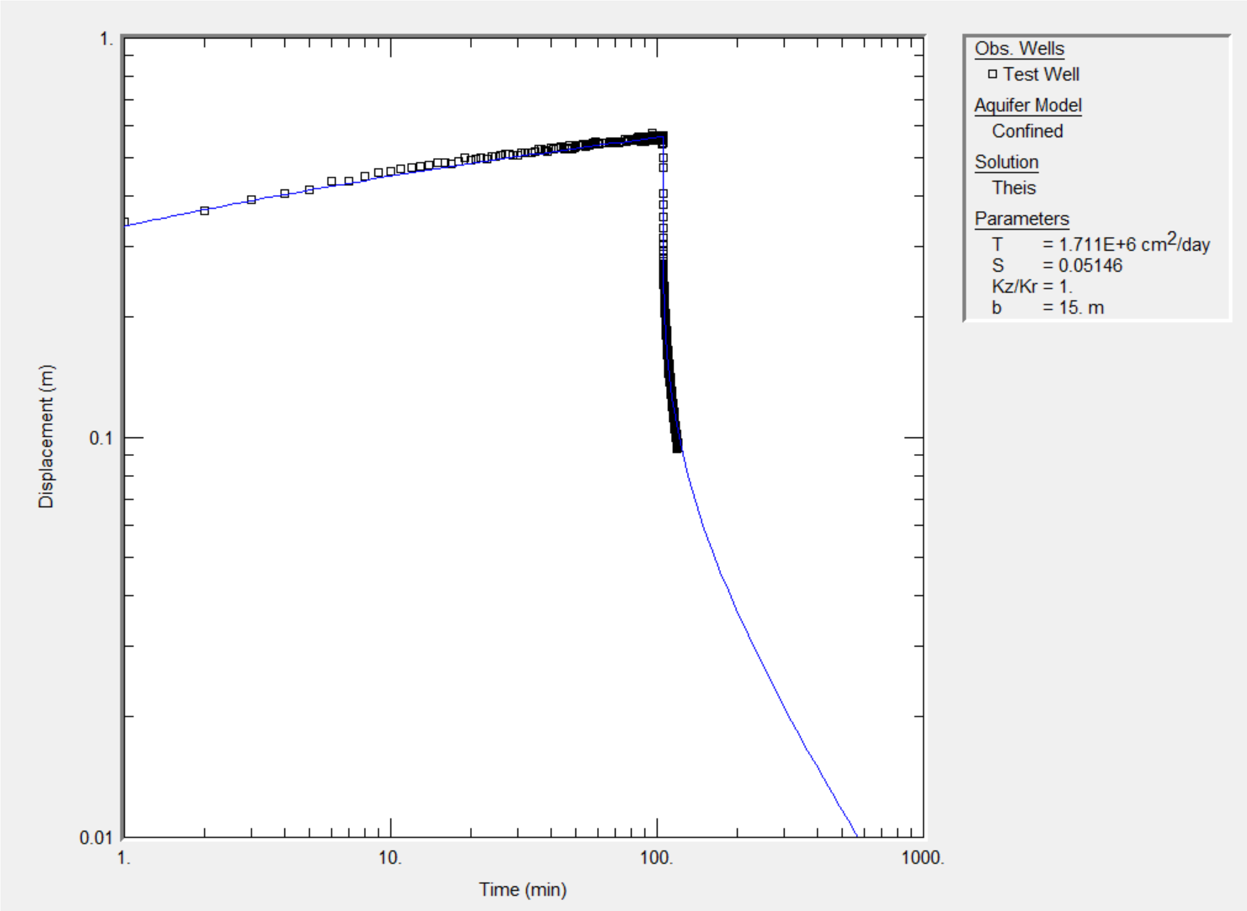

Figure 8: Theis solution for pump test data.

Sensor Records

Water level in the well ranged from 209.70 - 210.30 m above sea level (4.7 to 5.3 m below top of casing) over the three-month study period. Over short time spans (Figure 9), water level varied by as much as 20 cm, possibly due to a combination of Earth tides and pumping effects from nearby wells. The expected magnitude of the pressure response to Earth tides depends on a variety of factors, including formation compressibility and distance to drainage boundaries (Van Der Kamp, 1983). The expected effect of pumping depends on aquifer properties, distance to pumping wells, and pumping rates. The exact location of the nearest pumping well is unknown, but the well that supplies groundwater to Mirror Lake is likely within tens of meters of this observation well.

For comparison, water level in the lake ranged from 214.90 to 215.20 m above sea level over the three-month study period. Rain did occur during the monitoring period and would have contributed to changes in lake water levels. In November, the lake was drained to an elevation of lower than 214.41 m (exact elevations cannot be determined at times when the water level fell below the sensor). The lake remained empty while waiting on a repair to the clay liner, which was breached by a natural spring feature (Figure 10). Hydraulic head in the confined limestone aquifer always remained lower than in the lake by approximately 5 m.

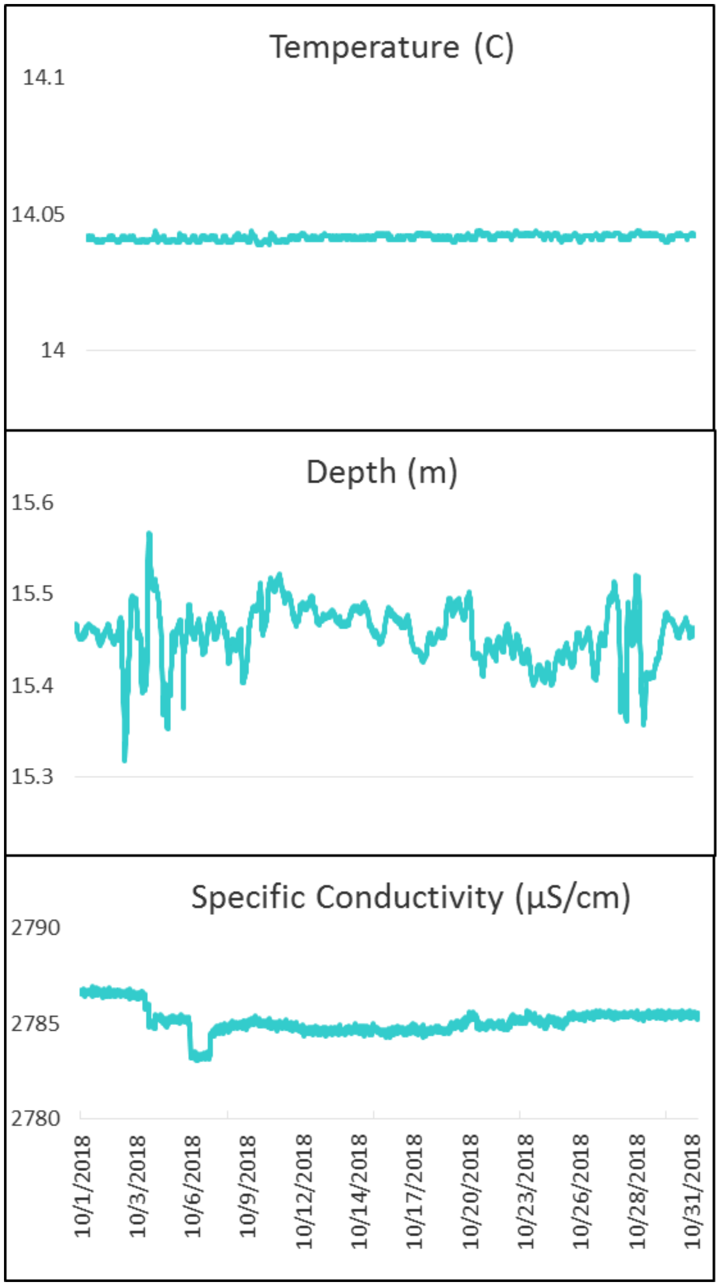

Figure 9: Temperature, water depth, and specific conductivity readings are shown for the month of October.

Figure 10: Spring feature in Mirror Lake.

Groundwater temperature remained at 14.4 °C ± 0.005 over the October monitoring period (Figure 9). For comparison, Mirror Lake temperatures varied from 30 °C to -2 °C due to seasonal and weather-related events. Some anomalous pressure spikes recorded in late November were likely artificial and created by water freezing in the sensor head.

Specific conductivity in groundwater was approximately 2785 µS/cm (or a TDS reading of 1811 mg/L) in October (Figure 9). For comparison, the TDS limit recommended for drinking water by the EPA is 500 mg/L. Specific conductivity in lake water declined from 708 µS/cm in late August to 371 µS/cm in November.

During the pump test, groundwater had a very low dissolved oxygen content near 0 mg/L, while the lake had much higher levels. Temperature was lower in the lake water than in the groundwater, and pH was slightly higher in the lake water (Table 1). Initial groundwater produced from the well had moderately elevated levels of dissolved oxygen, probably because this water was exposed to oxygen in the open well. As pumping proceeded, the dissolved oxygen concentration rapidly dropped to zero as groundwater was produced from the surrounding formation with no access to atmosphere. A slight drop in specific conductivity was also observed, suggesting that water originating from farther into the formation had a lower specific conductivity. This observation could imply that the high specific conductivity value in the borehole is due to factors such as grout interaction with stagnant water in the borehole.

Table 1: Water quality parameters recorded for Mirror Lake and the aquifer during the pump test.

	T (°C)	**DO (%)**	**DO (mg/L)**	**SpC (µS/cm)**	**C (mS/cm)**	**pH**	**ORP (mV)**
Lake Small Promenade	7	98	11.5	2502	1.64	7.37	-46.7
Lake Large Promenade	5.8	106	4.8	2503	1.58	7.75	-2.6
Produced Groundwater, 1 min after start of pumping	14.2	34	3.4	2503	1.99	6.19	-110.1
Produced Groundwater, 89 min after start of pumping	14.1	0	0	2477	1.96	6.84	-255.2

Discussion

Hydraulic Conductivity

The hydraulic conductivity (K) of the aquifer as calculated in the slug test (~2 x 10^{-2} cm/s) is within 2-fold of the estimate from the pump test (~1 x 10^{-2} cm/s). The greater slug test value could be due to conductive fractures or conduits in the near-well vicinity. Radius of influence was estimated from the method of Bouwer (1976) for the slug test and a derivation of the Cooper-Jacob equation for the pump test (Cooper and Jacob, 1946). The slug test has a smaller radius of influence, or measurement support volume, which is calculated to be 1.37 m. The estimated K from the slug test therefore reflects the near-borehole region and could be lower due to formation damage created during the drilling process. The pump test was conducted over more than an hour and drew water from an estimated radius of 100 m (assuming a reasonable specific storage value of 10^{-4} m^{-1}), rendering the K estimate from the pump test more representative of the surrounding aquifer.

K estimates compare well with other measurements in Columbus carbonate aquifers. For example, Cunningham et al. (1996) estimated K to be 7.0 x 10^{-3} cm/s using pump tests. The estimates are also in line with other limestone aquifers, including the Edwards Aquifer near Austin, Texas (Scanlon, 2003). Scanlon et al. (2003) modeled groundwater flow in the Edwards Aquifer and estimated K to be in the range of 10^{-2}-10^{-3} cm/s. Freeze and Cherry (1979) report typical K values for karst limestone between 10^{-4} and 10^{0} cm/s (Figure 11).

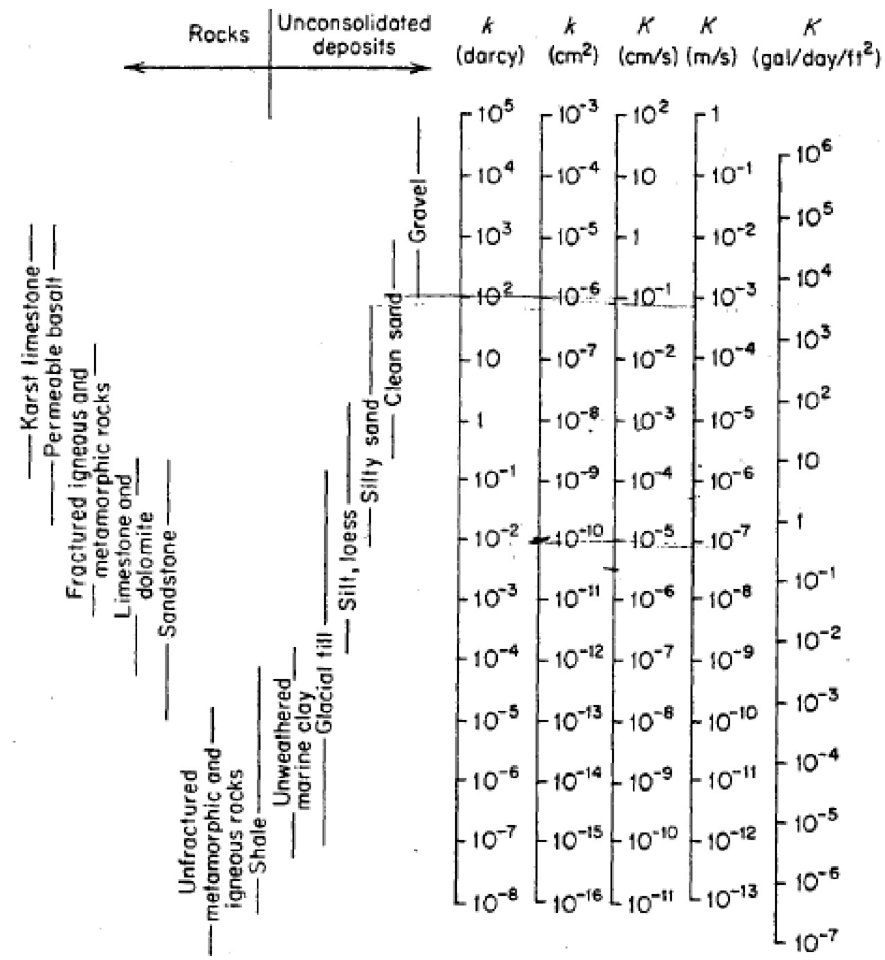

Figure 11: Hydraulic conductivity in different rock types (Freeze and Cherry, 1979).

Groundwater from the observation well is not suitable for drinking without further treatment. Throughout the pump test, a strong sulfur smell originated from produced groundwater. This odor is associated with microbial reduction of sulfate to hydrogen sulfide in the anoxic environment found in aquifers (Thomas, 2016). Specific conductivity values of 2480 µS/cm (TDS of around 1811 mg/L) were also quite high for groundwater, especially when compared with the EPA drinking water guideline for TDS of 500 mg/L. The anomalous drop in the specific conductivity in Mirror Lake throughout the autumn of 2018 may indicate that biotic or abiotic processes were altering the chemistry of produced groundwater that was introduced to the lake and exposed to the atmosphere. With the introduction of oxygen and particulate organic matter, much of the dissolved solids in produced groundwater water may react or sorb, which would lead to a steady decline in specific conductivity over time. Lake water and groundwater also differed strongly in temperature, which can have profound impacts on biological processes that alter water chemistry. The groundwater temperature was warmer than surface water during the fall and early winter, but this difference would be reversed during summer.

CONCLUSIONS

The groundwater observation well at Mirror Lake is completed in the confined portion of the Delaware and Columbus Limestone formations and has a high hydraulic conductivity of ~10^{-2} cm/s that is typical of Ohio karstic limestone aquifers. The groundwater is of marginal quality. Specific conductivity values are far above drinking water recommendations, and the groundwater has a distinct sulfur smell. Small water level fluctuations in the well (up to 20 cm over timescales of hours) may be due to the combined effects of local pumping, Earth tides, and aquifer recharge. The well is equipped to serve as a functioning observation well for years to come at The Ohio State University and will be an invaluable resource for future students to monitor groundwater resources on campus.

Recommendations for Future Work

Future studies should investigate the reason for the steady decline in total dissolved solids in the aquifer over time and perform a more complete geochemical analysis of groundwater. I recommend testing dissolved inorganic carbon (DIC), sulfate, sulfide, and nutrients to assess water quality in greater detail and determine whether there is any correlation with specific conductivity data gathered by the Troll-200 sensor. Sampling Mirror Lake's water chemistry over time (preferably following the draining and refilling of the lake) and then comparing results with the chemistry of water sources to the lake such as groundwater and storm water may provide additional insight into lake water chemistry dynamics.

Additional studies could be done to investigate groundwater flow in the region. To do this, one would need to establish additional observation wells (the more the better) that could be used to collect hydraulic head readings across the area. This would also allow for more accurate calculations of hydraulic conductivity at a regional scale through groundwater modeling.

Water level fluctuations would be another area for future study. The anomalous water fluctuations in the well could be related to recharge events associated with precipitation, Earth tides, pumping effects from nearby wells, or a combination of these factors. Looking at water level records over a larger time interval may provide clues. I would also suggest looking into pumping records for the well that supplies groundwater to Mirror Lake to try to explain water level fluctuations in the observation well.

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Appendix

Appendix A

DNR 7802.05e

WELL LOG AND DRILLING REPORT

Ohio Department of Natural Resources
Division of Water, 2045 Morse Road, Columbus, Ohio 43229-6605
Voice (614) 265-6740 Fax (614) 265-6767

Well Log Number: 2066915

Page 1 of 1 for this record.

WELL LOCATION

County FRANKLIN Township CLINTON

OSU
Owner/Builder

155 S OVAL MALL DR
Address of Well Location

City COLUMBUS Zip Code +4 43210

Permit No. ____ Section; ____ and/or Lot No. ____

Use of Well CATHODE PROTECT

Coordinates of Well (Use only one of the below coordinate systems)

State Plane Coordinates

N ☐ X ____ +/- ____ ft.

S ☐ Y ____ +/- ____ ft.

Latitude, Longitude Coordinates

Latitude: 39.998224 Longitude: -83.011888

Elevation of Well in feet: ____ +/- ____ ft.

Datum Plane: ☐ NAD27 ☒ NAD83 Elevation Source ____

Source of Coordinates: MAP-OTHERS

Well location written description:
ORTON HALL
EAST OF MIRROR LAKE
FOR GEOLOGICAL DEPT

Comments on water quality/quantity and well construction:

WELL TEST *

Pre-Pumping Static Level 17 ft. Date 3/1/2018

Measured from GROUND LEVEL

Pumping test method AIR

Test Rate 40 gpm Duration of Test 1 hrs.

Feet of Drawdown 13 ft. Sustainable Yield 40 gpm

*(Attach a copy of the pumping test record, per section 1521.05, ORC)

Is Copy Attached? ☐ Yes ☒ No Flowing Well? ☐ Yes ☒ No

PUMP/PITLESS

Type of pump ____ Capacity ____ gpm

Pump set at ____ ft. Pitless Type ____

Pump installed by ____

I hereby certify the information given is accurate and correct to the best of my knowledge.

Drilling Firm JAMISON WELL DRILLING, INC.

Address 258 CENTRAL AVE

City, State, Zip MANSFIELD OH 44905

Signed CYNTHIA GOLDEN (Filed Electronically) Date 3/5/2018

ODH Registration Number 0391

CONSTRUCTION DETAILS

Drilling Method: ROTARY

BOREHOLE/CASING (Measured from ground surface)

1 Borehole Diameter 10 inches Depth 69 ft.
Casing Diameter 6 in. Length 71 ft. Thickness 0.316 in.

2 Borehole Diameter 5.75 inches Depth 120 ft.
Casing Diameter ____ in. Length ____ ft. Thickness ____ in.

Casing Height Above Ground ____ ft.

Type 1: PVC
2: ____

Joints 1: Solvent
2: ____

SCREEN

Diameter ____ in. Slot Size ____ in. Screen Length ____ ft.

Type ____ Material ____

Set Between ____ ft. and ____ ft.

GRAVEL PACK (Filter Pack)

Material/Size ____ Vol/Wt. Used ____

Method of Installation ____

Depth: Placed From: ____ ft. To: ____ ft.

GROUT

Material Bentonite slurry Vol/Wt. Used 352 GALS H2O/800 LBS

Method of Installation Pumped w/Tremie pipe

Depth: Placed From: 69 ft. To: 0 ft.

DRILLING LOG*

FORMATIONS INCLUDE DEPTH(S) AT WHICH WATER IS ENCOUNTERED.

Color	Texture	Formation	From	To
BROWN		CLAY	0	5
BROWN		CLAY & GRAVEL	5	12
GRAY		SAND AND GRAVEL	12	36
LT. GRAY	SOFT	SHALE	36	66
		LIMESTONE	66	122
		Water Encountered At	118	120

Aquifer Type (Formation producing the most water.) LIMESTONE

Date of Well Completion 3/1/2018 Total Depth of Well 122 ft.

Completion of this form is required by section 1521.05, Ohio Revised Code - file within 30 days after completion of drilling.
Distribute copies of this record to Customer, and Local Health Deptartment.